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An Assessment of Current Risks, Fuels, and Potential Fire Behavior in the Sierra Nevada

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ABSTRACT

In this paper we examine the relative occurrence of large fires (risk), extent and pattern of fuel characteristics, and associated extreme fire behavior potential that currently exists for the Sierra Nevada Ecosystem core study area. The pattern of large fires (greater than 300 acres) was analyzed based on the spatial features of fuel type, population density, and weather zone. All three of these factors were found to be important in determining the size and likelihood of large fires. Risk as measured by the frequency, or return interval, of fires greater than 300 acres shows significant variation across the study area. Expected return intervals for such large fires range from greater than 10,000 years (i.e., extremely low risk) in high elevation, fuel discontinuous areas, to between 10 and 150 years in grass/brush fuel complexes coincident with zones of high ignitions, and long fire weather seasons. Fuels were mapped based on vegetation classifications for the region, and indicate a large percentage of the study area as having relatively high loads of surface fuels, particularly in the low- to mid-elevation western edge of the study area. Most of the shrub, pine/oak/grass, and pine/mixed conifer zones represent fuels with high associated hazard. This finding is supported by an analysis of potential fire behavior under severe fire weather. We found that for the SNEP area east of Sacramento, over half of the fuel covered landscape would support flame lengths in excess of 8 feet when burned under adverse conditions. This level of extreme fire behavior carries with it difficulty of control and likely undesirable effects on ecological and social resources in the Sierra.

INTRODUCTION

Much of the concerns regarding impending threats to the social and biological integrity of the Sierra Nevada are focused on fire and its capacity to do damage. In this light, an assessment of current conditions regarding fire risks, fuels, and hazard associated with extreme fire behavior are requisite to understanding why and where fire related problems exist in the Sierra. That is, to understand how fire might impact elements in Sierran ecosystems, we must understand where fires can be expected to occur, and should they occur how they might be expected to behave. In this paper we provide a spatial analysis of the probability of large fire occurrence (risk), fuel conditions, and how these fuels translate to hazard when burning under extreme environmental conditions likely to support large fires. In addition to providing base inputs into a larger regional scenario model (Sessions et al. 1996), these maps have inherent value as stand-alone products: explicit spatial delineation of current extent and magnitude of fire risk and hazard in the Sierras.

RISK

This procedure produces a map of the SNEP study area that shows the expected annual frequency of large (300+ acres) fires on a grid made up of 10 acre cells. Fire frequency is based upon ignition history, ratio of large fires to ignitions, and three point estimates of fire size (mean fire size) from the distribution of fire sizes in nine strata. Strata are based on life form, weather zone, and population density class.

Data

The CDF Strategic Planning Program provided State and National Forest fire point data to the SNEP team, which added additional fire point locations based on data provided by the National Park Service. The combined GIS fire point coverage has the following attributes:

1. Life form (Grass, Brush, Timber, Red Fir)
2. Weather Zone (1-5)
3. Population density class (Low, Medium, High)
4. Size of fire
5. Year of fire

Life Form - Fire behavior conditions can be markedly different in grass, brush, timber and Red Fir. Fires spread fastest in grass fuels because of the high surface to volume ratios. In brush, fires are hotter and may be more difficult to attack directly. Timber fires have the potential for crown fire conflagrations that can require multi-agency suppression efforts. Fire behavior at higher elevations may be less severe, such as in the Red Fir belt.

Weather Zone - Along with fuels, weather is a key driving factor in large fires. The SNEP study area includes five National Weather Service fire weather zones. Regional climatology, such as mean temperature, average relative humidity in summer, and wind patterns could affect the rate of large fires.

Population Density - Intermixed areas of urbanization and wildland could affect the rate at which large fires occur, and their ultimate extent. To some degree, fuel continuity is broken by the presence of roads and ornamental vegetation, affording more tactical advantages for fire suppression forces. Roads also provide accessibility for ground fire suppression resources. Detection and response can be rapid, with greater proximity to local suppression. In contrast, lower population density in the Sierra often means relatively remote locations, difficult terrain, limited road access, and more topographically diverse landscapes (e.g., steeper slopes).

The fire point data set is compiled from the following sources:

Source:		Period
CDF (Emergency Activity Reporting System)		1981-93
USFS (National Interagency Fire Management Integrated Database)		1970-93
NPS (converted from perimeter data)	SEKI:	1921-93
	YOSE:	1931-93

The combined data used in this analysis consists of 39,986 fire records from the period 1981-93. Of these fire records, 303 (0.76%) are large, which we defined for the purposes of the analysis as at least 300 acres in size. The CDF fire data records are origin points of vegetation fires geographically located as section (public land survey) centroids. The USFS data is similar, but after 1985 is referenced by latitude and longitude. For USFS and CDF data, any overlapping points (falling in the exact same location, i.e., section centroids) were redistributed randomly over the section. These data were used to generate a stratified set of landscape elements based on their occurrence of fires at least 300 acres in size (Table 1).

Table 1. Strata definitions for SNEP large fire analysis.

Stratum	Lifeform	Population	Wx_Zone	Fires_all	Fires_big	p_big
1	Grass/Brush	Low	North	4,829	39	0.008076
2	Grass/Brush	Not Low	North	2,191	10	0.004564
3	Grass/Brush	Low	South	2,808	66	0.023504
4	Grass/Brush	Not Low	South	760	14	0.018421
5	Timber	Low	North	13,321	64	0.004804
6	Timber	Not Low	North	7,299	23	0.003151
7	Timber	Low	South	5,433	74	0.01362
8	Timber	Not Low	South	1,407	7	0.004975
9	Red Fir	Low	South	937	6	0.006403

To derive Table 1, we looked at the percentage of large fires within 1) life forms; 2) population density classes; and 3) weather zones (Table 2).

Table 2. Fire size data by life form, population, and weather zone.

	Fires_all	Fires_big	p_big
Life Form			
Grass	4,808	45	0.94
Brush	5,780	84	1.45
Timber	27,251	166	0.61
Red Fir	1,938	6	0.31
Population			
Low	28,306	249	0.88
Medium	5,743	25	0.44
High	5,937	29	0.49
Wx_Zone			
Redding	8,015	59	0.74
Reno	4,756	23	0.48
Riverside	246	4	1.63
Sac	15,870	54	0.34
Fresno	11,099	163	1.47

Life Form (vegetation): We combined the grass and brush fire data, which have large relatively high percentages of large to total fires (0.94% and 1.45%), when compared to either Timber (0.61%) or Red Fir (0.31%). We did not combine the Timber and Red Fir because the percentages in Red Fir appear substantially lower than in Timber.

The vegetation data used to define Life Form follows:

National Parks:	Vegetation coverage themes from each National Park (USDI Park Service records)
State Lands:	Fire Management Analysis Zone (FMAZ) National Fire Danger Rating System fuel model (CDF records)
USFS R-5:	Determined from fuel model associated with each fire or from vegetation code ("org_cover") associated with each fire. Red Fir codes determined by overlay with USDA Forest Service vegetation strata information. (USFS Region 5 Remote Sensing Laboratory records).

Records that were not coded from the above information were overlayed on the statewide CALVEG database (about 7,400 out of 59,000+ records).

Population: Population density was determined by the FMAZ coverage, and is a rough approximation of the degree of structure protection effort needed during fire suppression. All

USFS population density was coded as Low. Population density classes collapse into two categories based on observations that the proportion of large fires in low population density (0.88%) is almost twice the proportion in high population density (0.45%) or medium population density (0.49%).

Weather: Weather Zone stratification was determined from National Weather Service Fire Weather Zones. We combined the Riverside and Fresno weather zones, in which the rate of large fires is clearly greater, and the remaining weather zones (Redding, Reno and Sacramento) in which the rate of large fires is much less. The more southerly located zones of Riverside and Fresno may be reflecting relatively drier and/or windier conditions.

Analysis

We calculated the average of the lowest 75%, middle 20% and upper 5% of fire sizes in each stratum. These averages can be thought of as having probabilities of .75, .2 and .05, respectively. These probabilities are used to determine the average annual frequency of large fires in each Section. The expected annual frequency for a large fire is calculated as the product of:

- the annual rate of ignition (total fires/year)
- the proportion of large fires (large fires/total fires)
- fire size probability (.75, .20, .05)

For example, if the rate of ignition is 0.5, the fire is in Stratum 1, and we want to know the rate of large fires for fires in the bottom 75% of the fire size distribution:

rate (fires)	*times*	*p(large)*	*times*	*p(window size)*	*equals*	*rate(879 acre fire)*
0.5	*	.008076	*	.75	=	.003028

Table 3 shows the data passed to the SNEP Geographic Information System. Listed to the right of each stratum number is the proportion, or probability, that a fire will be at least 300 acres in size, followed by the average fire size of the smallest 75%, middle 20% and top 5% of fire sizes in the data which comprise each stratum.

In the example, a large fire of 879 acres (Table 3 Stratum 1-next page) would have an annual frequency of about .003.

Expected Frequency of Large Fires

The data in Table 3 were used to develop a cumulative large fire probability grid. There are three "windows" (areas of analysis) for each of the 9 strata, for a total of 27 windows. For each stratum, we centered three moving windows (corresponding to the three large fire sizes) on each 10 acre cell, allocating to each cell within the windows the product of rate of ignition for the section, ratio of large fire to ignitions for the stratum associated with the section, and probability associated with the window (.75, .2, .05). When this procedure was completed for all nine strata,

Table 3. Probability and window size for large fire spatial analysis.

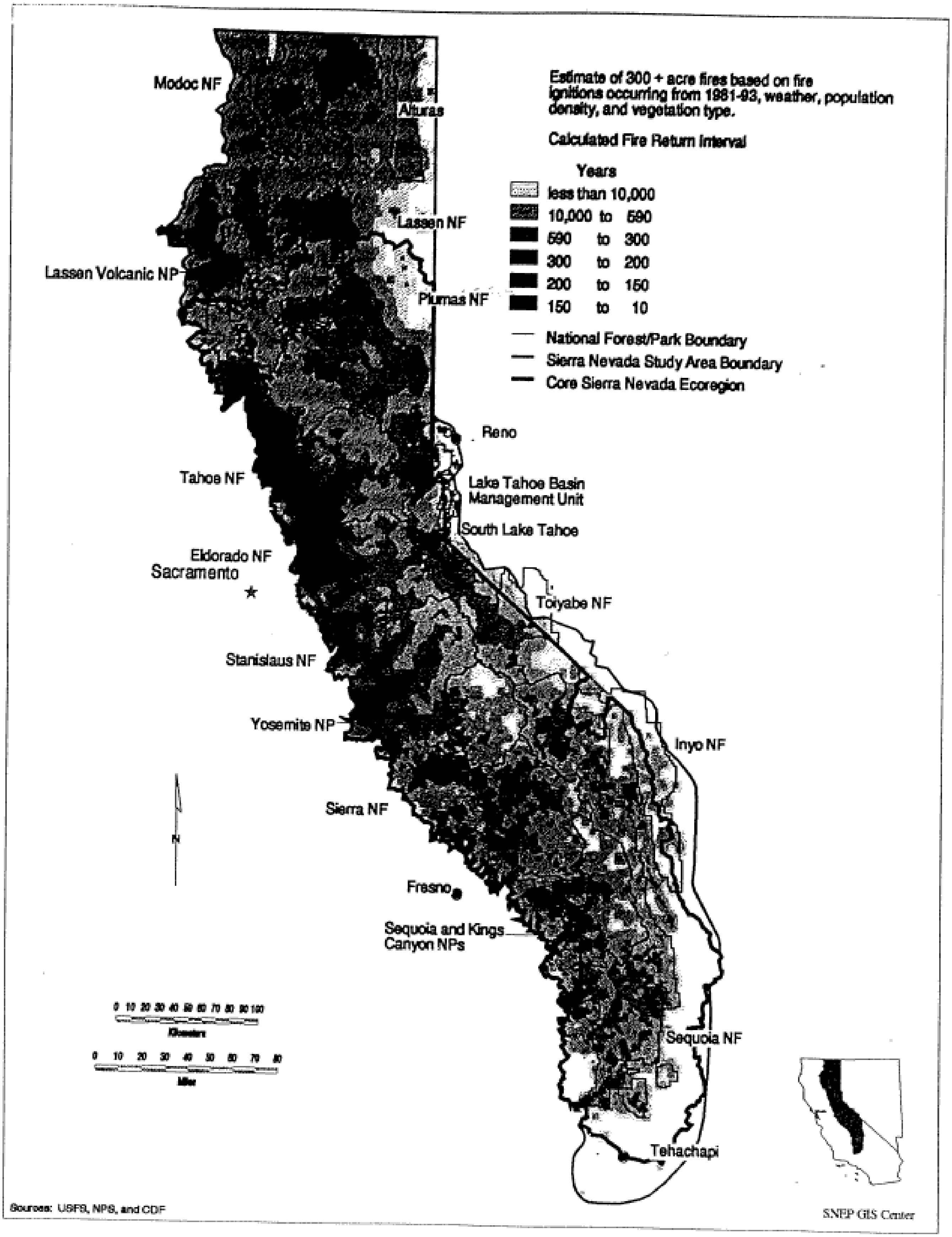
		p and Window Size (acres)		
Stratum	p(big)	p_size=0.75	p_size=0.2	p_size=0.05
1	0.008076	879	8,227	89,419
2	0.004564	659	32,780	6,400
3	0.023504	652	2,108	9,920
4	0.018421	533	5,444	25,932
5	0.004804	1,108	7,978	39,707
6	0.003151	882	9,087	18,000
7	0.01362	957	4,721	14,608
8	0.004975	420	588	630
9	0.006403	420	618	704

the probabilities were summed for each cell. Therefore, each cell location on the grid represents the summation of probabilities associated with at least 3, and as many as all 27 windows (Vol 1 Chapter 8). This figure presents the inverse of these occurrences, corresponding to the estimated fire return interval (in years) that correspond to these annual frequencies. The data are presented this way because it is easier to interpret relative large fire occurrence based on intervals as opposed to fractional rates on a per year basis.

The fire return intervals for each cell were grouped into six classes, ranging from an average of 10 to 150 years in areas of highest risk, to less greater than 10,000 years in areas of lowest risk (Figure 1). Much of the front country and Sierra Foothills falls into the highest risk category, while high elevation areas of sparse, discontinuous fuels show significantly lower rates of large fire incidence. Areas where the fuels are dominated by grasses and brush tended to have a higher incidence of large fires. An area of concentrated large fire risk is evident in the area to the Northeast of Sacramento, where all elements used in the analysis (fuel type, weather zone, and population density) tended to support large fire occurrence.

Discussion

The relatively short time span of the underlying data (13 years) has both advantages and drawbacks. On the plus side, these data are perhaps more reliable for describing current and near term future risk. The downside is that a paucity of fire incidence over substantial areas in the data period could translate into unreasonably low fire frequency estimates for these areas. One should assume that actual fire frequency in areas where fires were scarce in the data period may be higher than the map indicates. Additionally, the reader is cautioned in interpreting the classification of specific areas on the map. In that the model used to estimate the fire frequency is based on


Estimate of 300 + acre fires based on fire ignitions occurring from 1981-93, weather, population density, and vegetation type.
Calculated Fire Return Interval
Years
less than 10,000
10,000 to 590
590 to 300
300 to 200
200 to 150
150 to 10
National Forest/Park Boundary
Sierra Nevada Study Area Boundary
Core Sierra Nevada Ecoregion
Modoc NF
Alturas
Lassen NF
Lassen Volcanic NP
Plumas NF
Reno
Tahoe NF
Lake Tahoe Basin Management Unit
South Lake Tahoe
Eldorado NF
Sacramento
Toiyabe NF
Stanislaus NF
Yosemite NP
Inyo NF
Sierra NF
N
Fresno
Sequoia and Kings Canyon NPs
Sequoia NF
Tehachapi
0 10 20 30 40 50 60 70 80 90 100
Kilometers
0 10 20 30 40 50 60 70 80
Miles
Sources: USFS, NPS, and CDF
SNEP GIS Center

combined strata definitions, actual fire frequency for a particular area may be different than actual fire frequency due to averaging from other areas of like strata. However, we are confident that the relative frequency and regional trends evinced by the map are a reflection of actual likelihood of large fire, and are hence useful information in interpreting risk across the study area.

As is evident from the map, areas at the western fringe of the study area have higher probabilities of large fire. These areas correspond to areas of greater fine fuel concentration, more open stands and hence greater wind penetration to the surface, and higher levels of population resulting in greater sources of ignition. The low lying areas also have longer fire seasons where environmental conditions conducive to fire spread persist for longer periods than the higher elevation areas of the Sierra Nevada. These findings are similar to those of McKelvey and Busse (1996) who found a very strong influence of elevation on 20th Century fire occurrence for National Forest lands. Although the data used to generate this map was limited in temporal extent, it is evident that large fires are prevalent on lower areas and river corridors where a large influence of human use is evident. Further, open stands of grass and brush likely influence early fire progression, thus limiting the effectiveness of initial attack efforts, and contribute to the incidence of relatively large fires. The north-south relationship for fire weather needs further exploration, but given the relative prevalence of high fire danger weather throughout the state during summer months, it appears that fire risk is predominantly a function of interactions between fuel and ignition factors, all of which tend to increase as one moves down slope along the western front of the range.

FUELS

Fuels provide the energy source for fire, and characteristics associated with fuels strongly influence fire risk and behavior. Any classification of fuels implicitly assumes to characterize material as it burns (Hornby 1935). Thus, fuel models are really only interpretable when coupled with a fire behavior model that generates predictions of fire behavior using information about those fuels. As vegetation provides the basis for fuels, it is not surprising that fuel characteristics are often well correlated with vegetation composition and structure. A characterization of fuels in the SNEP study area not only provides the basis for estimating potential fire behavior under conditions favorable for large fires to occur, but also in conjunction with other vegetation data allow for refinement of potential vegetation/fuel modifications designed to reduce fire hazard.

To estimate fire behavior we must have information on three sets of variables: fuels, weather, and topography (Rothermel 1983). In the sense that we wanted to generate site-specific estimates of fire behavior, we needed fuel models that correspond with the use BEHAVE, the standardized model for site-specific fire behavior prediction in the United States (Andrews 1986). Consequently, the first step in generating fire hazard information is to define the kinds of fuel models represented in the Sierra Nevada. Although a group of 13 standard fuel models has been established to describe many fuel complexes common throughout North America (Anderson 1982) , the BEHAVE program allows the user to develop custom models to better represent actual fuel conditions than when using only the standard models (Burgan and Rothermel 1984).

We used a combination of standard and custom models to describe the fuels in the Sierra Nevada (Table 4). A complete description of fuel characteristics associated with these models can be found in Appendix A. It should be noted that in as much as fuel models are really only relevant in how they describe a system's capacity to burn, they consequently may appear to be fundamentally different that what they are describing. What is important to remember is that it is the reality of the output of the fire behavior prediction system that is important, whereby the fuel model, weather information, and topography interact to produce estimates of rates of spread, flame length, etc. (Rothermel 1983).

Table 4. Descriptions of fuel models used in classifying lands in the Sierra Nevada Ecosystem Project (SNEP) core study area.

FUEL MODEL #	DESCRIPTION
1	SHORT GRASS; common open grassland and woodlands.
2	TIMBER/GRASS Pine/, juniper and sagebrush woodlands.
4	CHAPARRAL; older decadent chamise/sclerophylous shrubs.
5	BRUSH; low shrubs and soft chaparral
6	DORMANT BRUSH; intermediate montane shrubs
8	TIMBER LITTER-- LIGHT; hardwoods, lodgepole pine, red fir
9	TIMBER LITTER -- MODERATE; dense white fir; underburned mixed conifer
10	TIMBER LITTER -- HEAVY; pine/mixed conifer with understory
12	SLASH--MODERATE; pine/mixed conifer with intermediate activity fuels
13	SLASH --HEAVY; pine/mixed conifer with very high loads of activity fuels
14	BURNED/PLANTATION; recently burned areas or immature plantations
16	CUSTOM PINE/MIXED CONIFER; litter with understory and activity fuels
18	CUSTOM SPARSE FIR; open jeffrey pine and true fir
20	CUSTOM RED FIR; Dense red fir with limited activity fuels
23	CUSTOM DENSE FIR; Dense mixed conifer/fir with understory and activity fuels
26	CUSTOM SIERRAN CHAPARRAL; intermediate between model 4 and 6.

Two key assumptions are important to recognize in this fuel modeling approach. One is that fire behavior related to a given fuel type (as represented by a fuel model) is actually a distribution of outputs based on the range of environmental conditions that the fuel may be exposed to while burning. A given fuel model will produce a wide range fire behavior outputs when modeled using the natural variation in fuel moistures, windspeeds, etc. The variation in accuracy of a fuel model across this distribution can lead to poor predictions when fuels are mapped for assessment under conditions that are not assumed by the mapper, or when the mapper is forced to choose from an alternative set of fuel models (Salazar 1987). Implicit in the fuel model mapping in this effort was the need to characterize fire behavior under a range of conditions -- from average fire weather where most ignitions take place, to extreme weather conditions under which large damaging fires are most likely to occur (Srauss et al. 1989).

We consequently employed a two-stage fuel modeling approach, where fuels were classified over the entire SNEP region assuming average weather conditions and using standard fuel models; and a second, more refined fuel modeling approach to reflect expectant fire behavior under extreme conditions. As most fires occur under the former, while most acres are burned under the latter conditions, both strategies have merit based on what element of the fire environment is at issue. The regional fuel map and the extreme fire behavior map both support an assessment of fire hazard in the Sierra Nevada where fuels form the basis of this hazard. Additionally, as fuels are the element in the fire environment most under the capacity for mitigation by management activities, these hazard maps indicate where this management might best be directed. However, in that land managers are really concerned with the effects of fire, and not the fire itself *per se*, hazard is only one part of a set of information required to make decisions on managing the land for desirable outcomes.

The second key assumption, related to the first, is that these fuel models only reflect surface fuels, and consequently only are relevant in their effect on surface fire spread. Although there are good relationships established between surface fire and propagation of crown fire in forested systems (Van Wagner 1977 and 1993, Alexander 1988), the fuel models themselves say nothing about crown fuels/fire, despite this being an important spread mechanism under severe conditions. This assumption underscores the need to understand what kinds of conditions, as well as what kinds of fire behavior indices are of concern in any analysis of fire hazard. As the estimates of fire behavior under extreme conditions carry with them expectations for initiation of crowning and spotting, it is incumbent upon the models to reflect the changes in fire potential relating to these mechanisms of fire spread not explicit in BEHAVE. That is, as fire weather gets more extreme, so does the potential for fire behavior mechanisms outside the explicit purview of the basic fire spread model. Our efforts to model surface fire spread must bear this in mind (Rothermel 1991).

Data and Methods

As stated, fuels often show a high degree of correspondence with vegetation. For example, where we have mature red fir, we can generally characterize the nature of the fuel complex. Using this relationship, we made use of the best available data on plant composition and structure for areas within the SNEP study area. For areas within the boundaries of the National Forest system, we used their strata coverage in the USFS CalVeg database. This classification was used because we perceived it as having the greatest utility in terms of vegetation structure information relevant to fuels, while providing complete coverage on National Forests lands. The strata database is actually an aggregation of the calveg label classification of vegetation type/size/density used for modeling forest growth and yield. In areas where non-productive lands lacked a strata label, or there were insufficient numbers of inventory plots to assign a strata label, we fell back on using the general vegetation type information in the calveg label to determine an appropriate fuel model. This coverage has been recently developed by USFS Region 5, and a summary of the techniques used to generate this coverage can be found in the Forest Inventory and Analysis Users Guide (USFS 1994).

Although a quality assessment of this data set is outside the scope of this report, it should be noted that this coverage was used as the basis for determining fuels on private lands within Forest boundaries where it existed, and consequently does not have representative inventory plots from these private lands. Consequently, although the same general procedure was employed whereby statistically valid samples of inventory plots were used to determine strata definitions, none of the plots were on private inholdings. A correspondingly lower level of accuracy likely accompanies the vegetation descriptions on these lands.

Using information based on ground surveys, field experience, and input from individual National Forests, the strata coverage was converted to fuel models using a crosswalk. In that the groupings of the calveg labels into strata labels were different forest by forest, and that actual strata-fuels relationships differed as well, each national forest was assigned its own crosswalk. An example crosswalk for the Eldorado National Forest is shown in Table 5. Although most crosswalks were quite similar, we chose to provide the opportunity for forest-specific interpretations of fuels derived from the vegetation inventory database.

TABLE 5. Vegetation-Fuel Model crosswalk for the Eldorado National Forest. "Regional Fuel Model" refers to fire behavior associated with normal fire weather, while "Extreme Fuel Model" refers to behavior associated with extreme fire weather conditions. Refer to Table 4 and Appendix A for fuel model descriptions.

Vegetation Classification *USFS strata/calveg:*	**Regional Fuel Model**	**Extreme Fuel Model**
A3S, A3P, A3N, A3G H3X, AC__, CH__, QC__, QO__	8	8
A1X, F0X, F1X, F2X, M0X, M1X, M2X, P0X, P1X, P2X, R0X, R1X	14	14
F3G, F3N, F3X, F4G, F4N	9	23
F3P, F3S, F4S	9	18
FNO	5	5
PNO, MNO	5	26
M3G, M3N, M3P, M3S, M3X, M4G, M4N, M4P, M4S, P3G, P3N, P3P, P3S	10	16
R3G, R3N, R3P, R3S, R4G, R4N, R4P, R4S	8	20
XNO, CC__	4	26
BS__	2	2
HG__, HJ__	1	1
BA__, WA__	0	0

Where the SNEP core study area was not covered by the CalVeg strata classification, two additional databases were used to define fuels. In the case of Yosemite and Sequoia/Kings Canyon National Parks, fuel model themes for use within the BEHAVE program have already been developed, and consequently where simply clipped out and placed into the fuels coverage. That is, these two National Parks had already developed fuel model maps, and we used them without any changes. In that both of these coverages have been used as the basis for fire spread modeling using FARSITE (Finney 1996), a spatial refinement of the BEHAVE model, it was assumed that the quality of these coverages was sufficient for our analysis.

The remaining areas not covered were mapped using the GAP analysis database as the basis for information regarding vegetation structure (Davis and Stoms 1996). These areas included private lands outside the Park/Forest boundaries, as well as large inholding areas within Forest administrative boundaries. We used the primary wildlife habitat relationship attribute ('WHR1') within this data set, to develop a similar vegetation/fuel model crosswalk as was used with the strata coverage (Table 6). Again, although a quality assessment of these data is beyond our scope here, it should be noted how the accuracy and precision of these data compare to the rest of the mapping effort. The minimum mapping unit of the GAP polygon coverage is roughly two orders of magnitude greater than the strata coverage, and there is no size and density information accompanying the WHR vegetation type classification. Consequently, we believe that although the GAP data does provide a means for assessing vegetation community type, it is less than an ideal coverage of vegetation in regard to classifying fuels. Without being able to further refine vegetation structure, we assumed that one crosswalk for all GAP-fuel models was sufficient for the entire SNEP area (Table 6).

One additional rectification was made to the fuels coverage, oweing to recent stand history that would likely affect fuel characteristics. Recent wildfire was used to reflect fuel complex changes that would not otherwise be accounted for in the base vegetation data. For areas on the National Forests, fire perimeter data created by the CALOWL EIS team, was used to delineate recent burned areas (USDA 1995). All fires less than 15 years old and greater than 100 acres in size were overlaid and assumed to be unique plantation polygons. Where data were available, large fires (>300 acres) on private land that burned in shrub and forest types were treated in a similar fashion. Fires occurring on grassland type fuels were assumed to result in no change in fuel model type. The intent of this procedure was to reflect the inherently low flammability and reduced fire hazard associated with plantations and new shrub regrowth (see Appendix A, model 14).

Results and Discussion

Putting all four sources of fuels information together results in a Regional Fuel Model Map for the Sierra Nevada (See Vol 1 Chapter 8). Of the approximately 18 million acres within the SNEP core study area, 25% of the area lacked basic vegetation data from which to derive fuels information. These areas were located primarily north of the Lassen National forest, and on the eastern edge of the study area. Neither Gap nor National Forest mapping projects extend to these areas.

TABLE 6. Vegetation-Fuel Model crosswalk for SNEP private lands using the GAP vegetation database (Davis and Stoms, 1996). "Regional Fuel Model" refers to fire behavior associated with normal fire weather, while "Extreme Fuel Model" refers to behavior associated with extreme fire weather conditions. Refer to Table 1 and Appendix A for fuel model descriptions.

Vegetation Classification *GAP whr1:*	**Regional Fuel Model**	**Extreme Fuel Model**
ADS, ASP, LPN, MHW, MRI, RFR, SCN, VRI	8	8
BOP, JUN, PJN, SGB	2	2
AGS, BOW, DSC, JST, PGS, VOW, WTM	1	1
CRC	4	26
LSG	5	5
DFR, EPN, JPN, WFR	9	23
CPC, MHC, PPN, SMC	10	16
BAR, LAC, OVN, RIV CRP, URB	0	0

Of the remaining areas, 11% is dominated by grass fuels (model 1), with an equal amount in mature shrub types (models 4, 5, and 6). Both of these fuel types are located predominantly in the western zone of the study area in the Sierra foothills. The balance of the landscape (53% or approx. 9.5 million acres) are dominated by forest types spanning the range from recently burned areas and plantations (model 14) through hardwood forests, to dense pine mixed conifer areas, to areas with significant levels of logging slash (models 12 and 13). The most abundant forested fuel type is the heavy pine/mixed conifer type (model 10) occupying 16%, or 2.8 M acres, followed by the lodgepole/red fir/ subapline type (model 8) occupying 14% (2.5 M acres). A sizeable percentage of the study area (11% or 1.9 M acres) is also occupied by the pine/grass type (model 2).

The regional picture of fire hazard reflected by this fuel map indicates a very high percentage of the low- to mid-elevation woodland and forest zone to be in a high hazard condition, capable of extreme fire behavior (including spotting) when burning under adverse weather conditions. This finding is supported in the more complex custom fuel modeling for extreme fire behavior that follows.

As is evident, there are significant scale related differences resulting from the different source vegetation data. Areas within the forest boundaries exhibit a finer grain, pixel-like character, while those adjacent private lands reflect the larger GAP vegetation polygons that they were derived from. Apart from any assessment of accuracy, it is evident that the precision within the Forest boundaries is greater than that of the adjacent lands, and any use of these data for subsequent analysis should be aware of this difference.

A portion of the region is mapped for fuels for prediction of extreme fire behavior, and is shown in Sessions et al. (1996) for the Eldorado National Forest and surrounding areas. This map depicts fuel models used to predict fire behavior under extreme environmental conditions. Of the approximately 1.46 M acres covered by this map, 15% (146,000 acres) are grass fuels, 6% (95,000 acres) are mature shrub dominated fuels, and 10 (150,000 acres) are non-fuel types (water, barren, agriculture, etc.). The remaining acres are all in forested fuel types, with the largest proportion again as heavy pine/mixed conifer (model 16) occupying 36% (531,000 acres). The pine-grass type also has a significant coverage of 9% (138,000 acres). The remaining forest types are relatively evenly distributed amongst dense fir (model 23), sparse fir (model 18) and red fir (model 20), each occupying approximately 3-6% of the land base, or roughly 50 - 95,000 acres. Finally, there is 4% (58,000 acres as recently burned areas or young plantations) 40% of which is a result of the 1992 Cleveland Fire apparent in the middle right of the figure.

These fuel type distributions correspond relatively well with the regional fuel classification, and indicate that when one considers that model 2, 16 and to a lesser extent model 23, as being high hazard forest fuels where surface fuel characteristics coupled with high canopy density and a high preponderance of ladder fuels either from understory development or immature conifer cohorts, that roughly one half of the land base supports fuel and vegetation characteristics that indicate high crown fire potential. Although the fuel models are only useful in predicting surface fire behavior, it must be understood that the vast majority of crown fire behavior activity in California is strongly linked to surface fire intensity, and any effective treatment of this problem implies surface fuel treatments in addition to stand density modifications (Alexander 1988, Sapsis and Martin 1994).

Another interesting aspect of the pattern of extreme fuels across the land is made apparent when comparing Forest Service lands with adjacent state lands. Although not all private inholdings within the forest are reflected, there is roughly a 50-50 split in land ownership for the Eldorado/private lands map. The vast majority of grass and pine/grass fuels occurs on private land, while the vast majority of the densely forested fuel types lie within the National Forest. Along the western margin of the National forest there is a mixture of brush, dense conifer, and low elevation hardwood/conifer that presents a particular hazard when juxtaposed with urbanization of this area. Almost universally, the ecotone between the brush/hardwood and the pine belt supports high hazard surface fuels, extensive mid-story vertical fuels (i.e., ladder fuels), and crown densities sufficient for dependent crown fire development (Van Wagner 1977, Alexander 1988). These features contribute to making this area of particular concern in the event of fires occurring during extreme weather.

EXTREME FIRE BEHAVIOR

In as much as most acres currently being affected by wildfires are by fires exhibiting high rates of spread and other characteristics associated with extreme fire behavior, we recognize the need to estimate quantifiable descriptors of fire behavior likely in the event of severe wildfire. Although the occurrence of environmental conditions associated with extreme fire weather are different throughout the SNEP area, and are reflected in different rates of burning, the relationship between fire weather, fire behavior, and adverse impacts on resources is common across the range. That is, extreme fire behavior always occurs under conditions that will support such fire behavior, and these kinds of fires tend to be difficult to bring under control. Further, these kinds of fires are likely to generate the greatest degree of fire effects on resources -- tree mortality, soil erosion, etc. Consequently, it is highly desirable from an assessment standpoint to be able to estimate fire behavior under those conditions that are likely to result in large damaging fires, i.e., those occurring under extreme fire weather.

Data and Methods

Fire behavior estimates were made using the BEHAVE computer program (Andrews 1986). We chose to describe fire behavior in terms of flame length for a number of reasons. Although this measure represents only one index of fire behavior, we chose to use it as a general indicator of fire behavior in that it gives information that is generally understandable to the average person, and has been used to infer both difficulty of control and ecological effects. Specifically, suppression tactics and fire induced mortality on conifers have been directly related to flame length (Albini 1976, Ryan and Reinhardt 1988). Additionally, surface fire flame length is an important consideration in conditions leading to initiation of crown fire (Van Wagner 1977).

Inputs required to generate estimates of flame length within BEHAVE are fuels (models), weather (fuel moistures and windspeed) and slope. Using the fuel models defined previously we linked weather and slope information into classes, ran individual BEHAVE runs for each discrete combination, then linked the outputs back to those grid cells having the appropriate combinations of fuel, weather and slope class.

We assumed that estimates of extreme fire behavior based on wind and slope driven frontal fire behavior (i.e., maximum possible outputs where wind and slope work in parallel) would offer the best single estimate of potential fire behavior, as head fires dominate the burn distribution. As extreme fire behavior is almost unilaterally associated with high winds where much of the slope effect is dampened and actual fire spread is driven by overhead wind driven spotting, we chose to work solely on identifying likely surface fire estimates for the heading front, then make inferences regarding crown fire initiation (Sessions et al. 1996).

Slope influences on fire behavior were assessed by using the digital elevation model (DEM) in the GIS database to separate the landscape into grids of less than 40% and greater than 40%, and ran individual fuel model/weather scenarios at 20% and 60% slope to estimate midpoints for these classes.

Weather inputs were generated using National Fire Danger Rating System (NFDRS) methodology for sorting weather data based on danger rating indices of fire behavior. We used the pcFIRDAT and pcSEASON computer programs to sort historic weather station data based on the 97% worst weather as indicated by the distribution of the Burning Index (BI) (CDF 1994). These programs are derivatives of the FIRE FAMILY group of programs developed in by the US Forest Service (Main et al . 1982). The BI is a danger rating index related to both rate of spread and energy release, and hence serves as the closest analog to flame length when viewed as a predictor of potential fire behavior (Deeming et al. 1977). Each daily reading of weather inputs from a station translates to an estimated BI, which are then summed into a cumulative distribution that can be sorted. As extreme fire weather is often considered to occur during the worst 3% of cases, we choose this as the cutoff point in the distribution. Although all estimates of extreme weather were based on 2 pm readings, usually associated with peak daily severity, fire weather patterns associated with large scale, high intensity fires commonly occur during sustained period of high fire danger where similar readings are sustained for longer periods of time. Thus, the "worst-case" design of the NFDRS system can be though of as compatible with the objective of determining appropriate weather conditions supporting extreme fires.

The DEM was also used to separate out two aspect classes -- a northeast and a southwest class, from which adjustments to the base weather data were made. Additional adjustments based on vegetation type were also included to incorporate elevational changes in weather as it deviated from the location of the representative weather station. For instance, Red Fir occurs at significantly higher elevations than the Bald Mountain weather station used to assess fire weather for the Eldorado National Forest area, and consequently should reflect higher fuel moistures than that estimated for vegetation types near the elevation of the station. Although a variety of means were available to do this, we relied on expert judgement and experience in the forest to make these adjustments. The final modifications to the weather data concerned the effect of stand structure on windspeed. The data coming out of the fire weather records reflects measurements taken at 20 feet above the surface, and BEHAVE requires mid-flame estimates for this factor. We used the adjustment table based on 20 ft wind, fuel model and canopy cover (Albini and Baughman 1979). An example of the base weather inputs and vegetation/fuel model adjustments in shown in Table 7.

Results and Discussion

Flame length estimates for the Eldorado National Forest and surrounding private lands span the spectrum from less than 2 feet in high elevation red fir/lodgepole pine types, to greater than 18 feet in the low elevation chaparral types (Figure 2). We broke the flame length outputs into 4 feet increments for the black and white figure shown here, whereas a more precise rendering of this information can be found in 2 ft increments and in color, in Sessions et al. (1996). Both figures indicate the significant extent of extreme fire behavior potential that exists in this region.

Of the 1.46 million acres depicted, 10% is covered by non-fuel, hence has no representative flame length. The largest flame length class is the 8-12 ft. category, covering 40% of the land area. The vast majority of this class is found in the lower elevation transition zone from grey pine/oak/brush through the body of the pine/mixed conifer zone up to about 5,000 ft elevation (Figure 2). As was stated previously, fire behavior in this class indicated a high resistance to control, and a high capacity for resource damage.

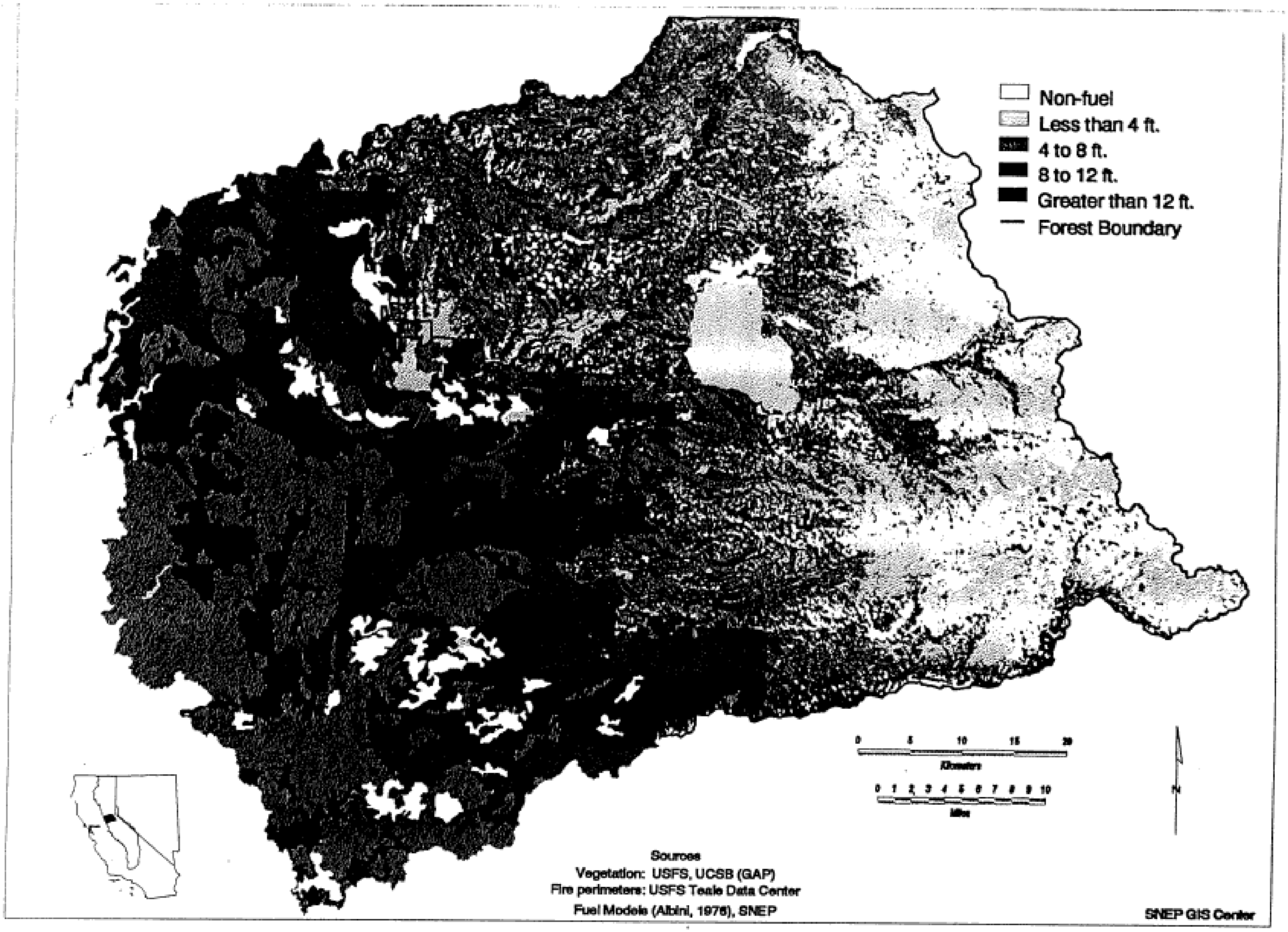

Non-fuel
Less than 4 ft.
4 to 8 ft.
8 to 12 ft.
Greater than 12 ft.
Forest Boundary
Sources
Vegetation: USFS, UCSB (GAP)
Fire perimeters: USFS Teale Data Center
Fuel Models (Albini, 1976), SNEP
SNEP GIS Center

Table 7. Environmental inputs used for fire behavior calculations on the Eldorado National Forest and surrounding areas. These environmental parameters correspond with model input requirements when using the BEHAVE fire prediction model.

Base Inputs	
1hr fuel moisture:	3%
10hr fuel moisture:	4%
100 hr fuel moisture:	5%
live woody fuel moisture:	70%
live herb fuel moisture:	30%
Wind:	6 mph
Wind Vector:	0 degrees offset from slope
Adjustments :	
All alpine (A strata) types:	+2% dead fuel moisture +1 mph south slopes -2 mph north slopes
Red Fir (R strata) types:	
all except X	+3% dead fuel moistures -3 mph on north slopes
X (plantation)	+2% dead fuel moistures
Dense Fir (F strata) types:	
N, G, and 3X classes	+1% dead fuel moistures, -2 mph on south slopes +2% dead fuel moistures -4 mph on north slopes +30% live fuel moistures
Sparse Fir	
S, P classes	+1% dead fuel moistures, +1 mph on south slopes +2% dead fuel moistures -1 mph on north slopes
Fir Plantations and FNO	No Change
Dense Pine (P strata) and Mixed Conifer (M strata) types:	
N, G, 3X	+1% dead fuel moisture -1 mph on south slopes -2 mph on north slopes
Sparse Pine and Mixed-Conifer types:	
S, P	+ 1 mph on south slopes, - 1 mph on north slopes
Pine and mixed Conifer Plantations and PNO, MNO	No Change
All GAP and non-Timber strata:	No Change

When we superimpose this coverage onto development patterns, urban-interface issues such as human health and safety and potential housing loss become apparent.

The next most abundant flame length class is the 4-8 ft. grouping covering 29% of the land base. An additional 5% of the area --mostly areas covered by brush fuels-- is expected to support flame lengths greater than 12 ft. Hence, fully three-quarters of this area is expected to burn with flame lengths greater than 4 feet when burning under severe fire conditions. Only 15% of the area supports predictions of flame lengths less than 4 feet.

Clearly, the 45% (632,000 acres) that is estimated to burn with than 8 foot or greater flames presents a high potential for stand replacing fire, whether through crown fire or through other mechanisms of tree mortality. Additionally, the 8 % in the 6-8 foot class represents areas of lesser but still significant potential for large, damaging fires. Thus, when non-fuel areas are accounted for, more than half the landscape fuel covered landscape is expected to demonstrate extreme fire behavior if burning under severe weather.

These findings indicate that not only are crown fires expected to occur under these conditions, certain spatially limited fuel modifications (e.g., fuel breaks) may offer only limited utility as a tactical point of control for wildfire suppression (Sessions et al. 1996, Van Wagtendonk 1996, Weatherspoon and Skinner 1996). Thus, the only significant means by which large area mitigation of extreme fire behavior and potential for reduced resource damage lies with area based treatment methods.

When coupled with the information presented on risk here and in McKelvey and Busse (1996), these findings on hazard present a significant issue of concern for Sierra Nevada Ecosystems. Although findings on fire size and abundance indicate no trends in increasing amounts of fire in the Sierra (Erman and Jones 1996) what we may be seeing is an increase in fire severity resulting from stand and fuel condition changes resulting from harvesting and fire suppression. Further, with clear climate induced responses and an uncertain future in regard to incidence of severe fire weather, the prospects for fire related damage from extreme wildfire loom large. Fuel conditions in much of the Sierra Nevada support the potential for large fires exhibiting extreme fire behavior with likely undesirable effects. Future management of the region would be well served to understand this, and make hazard reduction an objective in any land management strategy.

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Appendix A. Fuel model descrpitions used in classifying fuel characteristics and fire behavior modeling for the Sierra Nevada Ecosystem Project Study Area. Fuel Model numbers less than 1 through 13 reflect standard models used nationwide (Albini 1976), while fuel model numbers greater than 13 reflect custom models developed specifically for this study. Heat of combustion for all fuel models is assumed to be 8,000 BTU/lb. Interested readers wishing to understand the nature of these fuel characteristics, and how they affect fire behavior, are directed to Rothermel (1983), Burgan and Rothermel (1984) and Burgan (1987).

Fuel Model 1 – Short Grass

Loading (t/a)/surface-to-volume ratios (1/ft):

1hr	0.74/3500
10hr	
100hr	
live	

Depth (ft): 1.0

Moisture of Extinction(%): 12

Fuel Model 2 – Timber, Grass and Understory

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	2.00/3000
10hr	1.00/109
100hr	0.50/30
live	0.50/1500

Depth (ft.): 1.0

Moisture of Extinction (%): 15

Fuel Model 4 – Chaparral

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	5.01/2,000
10hr	4.01/109
100hr	2.00/30
live	5.01/1,500

Depth (ft.): 6.0

Moisture of Extinction (%): 20

Fuel Model 5 – Brush

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	1.00/2,000
10hr	0.50/109
100hr	
live	2.00/1,500

Depth (ft.): 2.0

Moisture of Extinction (%): 20

Appendix A (cont.):

Fuel Model 6 -- Dormant Brush

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	1.50/1,750
10hr	2.50/109
100hr	2.00/30
live	

Depth (ft.): 2.5

Moisture of Extinction (%): 25

Fuel Model 8 -- Closed Timber Litter/Hardwood Forest

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	1.50/2,000
10hr	1.00/109
100hr	2.50/30
live	

Depth (ft.): 0.2

Moisture of Extinction (%): 30

Fuel Model 9 -- Hardwood Litter

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	2.92/2,000
10hr	0.41/109
100hr	0.15/30
live	

Depth (ft.): 0.2

Moisture of Extinction (%): 25

Fuel Model 10 -- Timber and Understory

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	3.01/2,000
10hr	2.00/109
100hr	5.01/30
live	2.00/1,500

Depth (ft.): 1.0

Moisture of Extinction (%): 25

Fuel Model 11 --Light Logging Slash

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	1.50/1,500
10hr	4.51/109
100hr	5.51/30
live	

Depth (ft.): 1.0

Moisture of Extinction (%): 15

Fuel Model 12 -- Medium Logging Slash

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	4.01/1,500
10hr	14.03/109
100hr	16.53/30
live	

Depth (ft.): 2.3

Moisture of Extinction (%): 20

Fuel Model 13 -- Heavy Logging Slash

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	7.01/1,500
10hr	23.04/109
100hr	28.05/30
live	

Depth (ft.): 3.0

Moisture of Extinction (%): 25

Fuel Model 14 -- Plantations/Young Brush

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	1.00/2,000
10hr	0.50/109
100hr	
live	2.00/1,500

Depth (ft.): 0.2

Moisture of Extinction (%): 25

Appendix A (cont.)

Fuel Model 16 – Mixed Conifer/Pine – Heavy

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	3.00/2,000
10hr	2.00/109
100hr	3.00/30
live	2.00/1,500

Depth (ft.): 1.5

Moisture of Extinction (%): 25

Fuel Model 18 – Mixed Conifer/FIr Low Density

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	0.80/2,000
10hr	0.50/109
100hr	2.00/30
live	1.50/1,500

Depth (ft.): 1.5

Moisture of Extinction (%): 25

Fuel Model 20 – Red Fir

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	2.00/2,000
10hr	0.41/109
100hr	
live	

Depth (ft.): 0.25

Moisture of Extinction (%): 25

Fuel Model 23 – Mixed Conifer/Fir – High Density

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	2.00/2,000
10hr	1.50/109
100hr	3.00/30
live	2.00/1,500

Depth (ft.): 1.3

Moisture of Extinction (%): 25

Appendix A (cont.)

Fuel Model 26 Sierran Chaparral

Loading (t/a)/surface-to-volume ratios (1/ft)

1hr	2.70/2,000
10hr	2.70/109
100hr	1.80/30
live	3.6/1,500

Depth (ft.): 3.6

Moisture of Extinction (%): 25